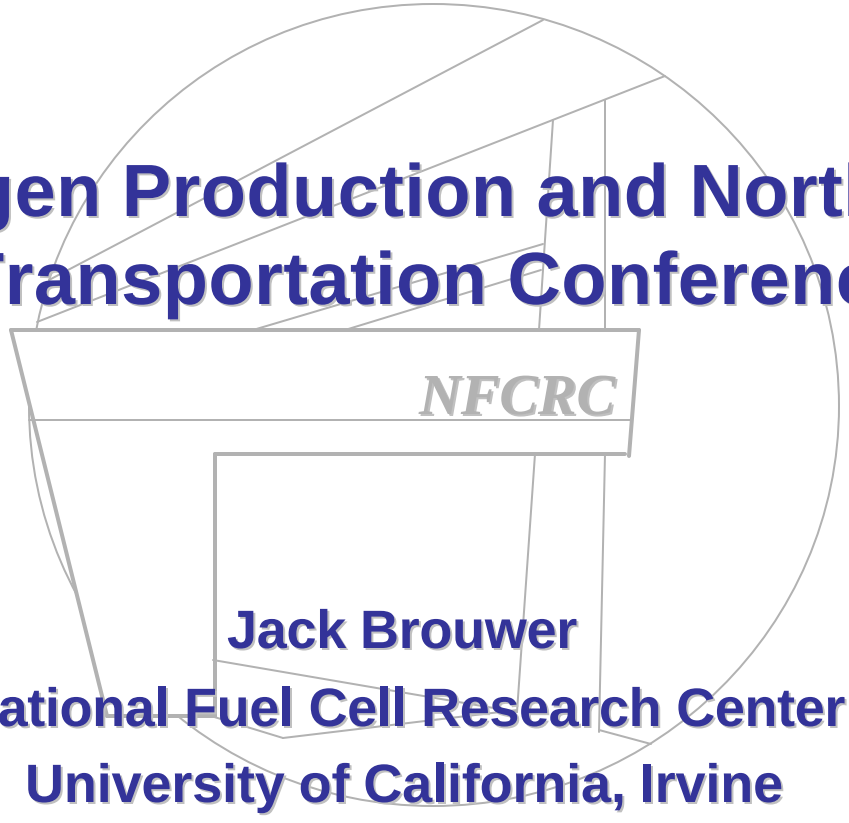
Status of Fuel Cell Technology

Hydrogen Production and Northwest Transportation Conference



Jack Brouwer
National Fuel Cell Research Center
University of California, Irvine

June 16, 2003

Presentation Outline

Fuel Cell Introduction

Fuel Cell Applications

Some Recent Developments

- Stationary Power
- Transportation
- Portable Power
- Other

Summary

FUEL CELL INTRODUCTION

CONCEPT

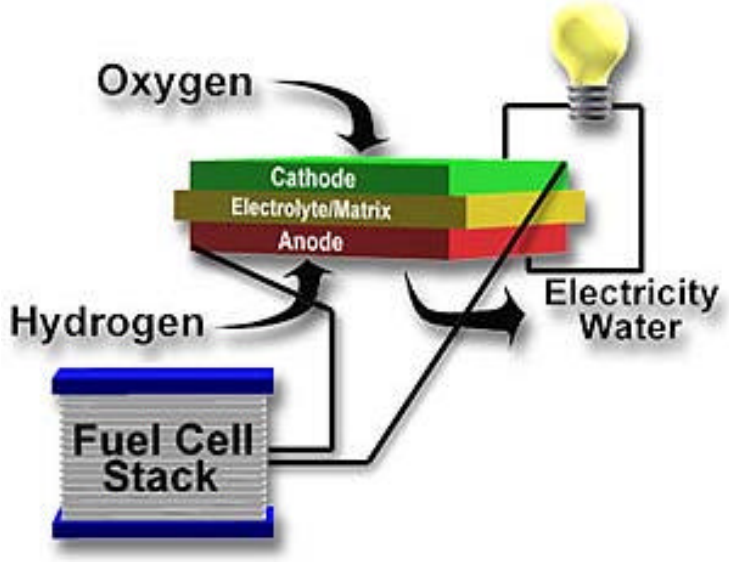
Electrode/Electrolyte Assemblies (similar to battery)

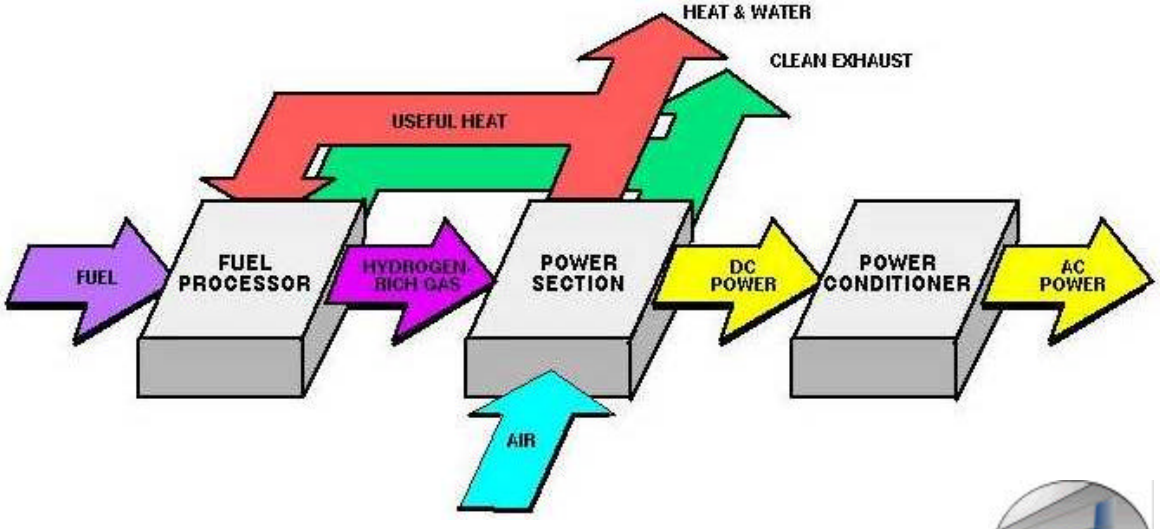
Continuous electricity production

- **Fuel and oxidant provided to separate chambers**

"Stack" - Increase Voltage/Current to Useful Levels

"System" – Make applicable to current fuels and end-use





FUEL CELL INTRODUCTION

Fuel Cell Types (Characterized by Electrolyte Material)

FUEL CELL TYPE	*ELECTROLYTE*	*OPERATING TEMPERATURE*	*CHARGE CARRIER*	*APPLICATION & FUEL COMMENTS*
AFC	POTASSIUM HYDROXIDE	~ 80°C	OH^-	Space Pure H_2, CO, CO_2 intolerant
MCFC	MOLTEN ALKALI CARBONATES	~650°C	$CO_3^=$	Stationary Power Fuel flexibility
PAFC	PHOSPHORIC ACID	~200°C	H^+	Stationary Power, Transportation Relatively pure H_2
PEMFC	ION EXCHANGE MEMBRANE	~50°C	H^+	Transportation Pure H_2, CO intolerant
SOFC	SOLID METAL OXIDE	~1000°C (HIGH) ~ 650°C (LOW)	$O^=$	Stationary Power, APU Fuel flexibility

FUEL CELL INTRODUCTION

ADVANTAGES:

- Zero To Ultra-low Pollutant Emissions (NOx, SOx, HC, CO)
- High Fuel-to-Electricity Conversion Efficiency
- Low Noise
- Modularity and Applicability to Diverse Applications
  - stationary, mobile, portable, …
- POTENTIAL FOR:
  - High Reliability (No/Few Moving Parts)
  - High Energy Density (e.g., compared to batteries)
  - Power Quality
  - Siting/Licensing Ease
  - Distributed Generation Benefits

DISADVANTAGES:

- Cost, Cost, Cost
- Track Record
- Low Power Density (e.g., compared to gas turbine engine)
- Reliability, Availability, Maintainability, Durability And User Friendliness (RAMDU)

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FUEL CELL APPLICATIONS

STATIONARY / DISTRIBUTED POWER

- Residential/Commercial/Industrial Appl.
- Backup Power
- Remote Power
- Premium Power

TRANSPORTATION: HEAVY / LIGHT DUTY VEHICLES

- Buses / Trucks
- Passenger Vehicles
- Locomotives / Shipping

PORTABLE POWER BATTERY REPLACEMENT

Consumer Electronics	Small Motors
Laptop Computers	Boating
Cellular Phones	Lawn Mower
Camcorders, etc.	Tools, etc.

FUEL CELL APPLICATIONS

DISTRIBUTED GENERATION

Stage: Initial Commercialization

- **High-cost Local Power**
  - **e.g., 25-30 Million Homes (> $0.10 / kWhr)**
  - **@ $0.07-0.08/kWhr, $500 Annual Savings**
- **New Buildings, Homes, Business**
  - **Most have natural gas connection**

Possible Developing World Market

- **No Electricity - 2 Billion People**
  - **DG Paradigm may offer cost savings (cellular phone analogy)**

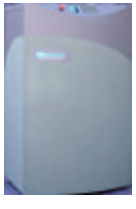
Plug Power

Hydrogenics

FuelCell Energy

UTC Fuel Cells

GM / Hydrogenics



Idatech

Nuvera

Siemens Westinghouse

Ballard-Ebara

FUEL CELL APPLICATIONS

DISTRIBUTED GENERATION

Warranteed/guaranteed products available today from a wide variety of manufacturers, for example:

- UTC Fuel Cells – 200kW PAFC
- Toshiba – 200kW PAFC
- Fuji – 200kW PAFC
- FuelCell Energy – 250kW MCFC
- Plug Power – 5kW PEMFC
- Avista Labs – 1kW PEMFC

Products available as prototypes and emerging as products from, for example:

- SWPC – SOFC
- Nuvera – PEMFC
- Hydrogenics – PEMFC
- Idatech – PEMFC
- Ballard – PEMFC
- GTE – SOFC
- FCTL – SOFC
- UTC FC – PEMFC
- Acumentrics – SOFC
- Anuvu – PEMFC
- Astris Energy – AFC
- CFCL – SOFC
- GE – SOFC
- Vairex – PEMFC
- SOFCo – SOFC
- Delphi – SOFC
- Fuji – PEMFC
- Hitachi – PEMFC
- Sanyo – PEMFC

Note: not comprehensive lists

FUEL CELL APPLICATIONS

TRANSPORTATION

- Buses
- Passenger Vehicles / Light Trucks
- Electric Bikes
- Golf Carts
- Trucks
- Shipping/Submarines
- Locomotives
- Snowmobiles
- Aircraft
- Other

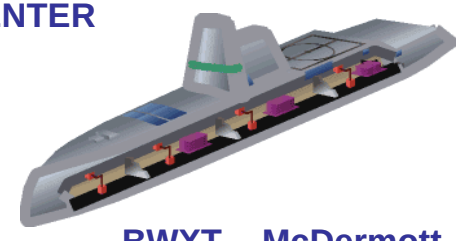
TOYOTA FCHV

NEBUS

SCHATZ ENERGY RESEARCH CENTER

BOEING

MANHATTAN SCIENTIFICS



BWXT – McDermott U.S. Navy

BURLINGTON NORTHERN

FORD FOCUS

POLARIS 440 PRO X RACER

GERMAN TYPE U 212

FUEL CELL APPLICATIONS

TRANSPORTATION

Nissan

Toyota, RAV4
(PEMFC)

DaimlerChrysler Necar4

Jeep Commander

Ford P2000

FUEL CELL APPLICATIONS

TRANSPORTATION

Ford Model U

Daihatsu MOVE

DaimlerChrysler – Necar5

GM-Opel FedEx FCV

Honda FCX

Toyota Fine S

FUEL CELL APPLICATIONS

TRANSPORTATION

GM Opel Hydrogen 1

Honda FCX V3

DaimlerChrysler & Ford

Mazda Demio

Nissan FCV

Toyota FCHV

Ford P2000 H2

BMW 700 Series

GM Precept

FUEL CELL APPLICATIONS

BUSES

DaimlerChrysler NeBus

UTC Fuel Cells – Georgetown Bus

Ballard - Vancouver

Mercedes-Benz Citaro 30

FUEL CELL APPLICATIONS

BUSES

Citaro FC Bus

DaimlerChrysler NeBus

Ballard – Chicago Bus Fleet

UTC Fuel Cells – Recent Georgetown Bus

FUEL CELL APPLICATIONS

OTHER FUEL CELL VEHICLES

Coval H2

Energy Partners

Energy Partners

Manhattan Scientifics

H Power Corp.

FUEL CELL APPLICATIONS

PORTABLE POWER

- Low Power Remote
- PDAs
- Pagers
- Wireless Handsets/ Cellular Markets
- Laptop Computers
- Power Tools

Ball Aerospace

Casio

Toshiba

Smart Fuel Cells

Fraunhofer ISE

Ballard Power Systems

Manhattan Scientifics

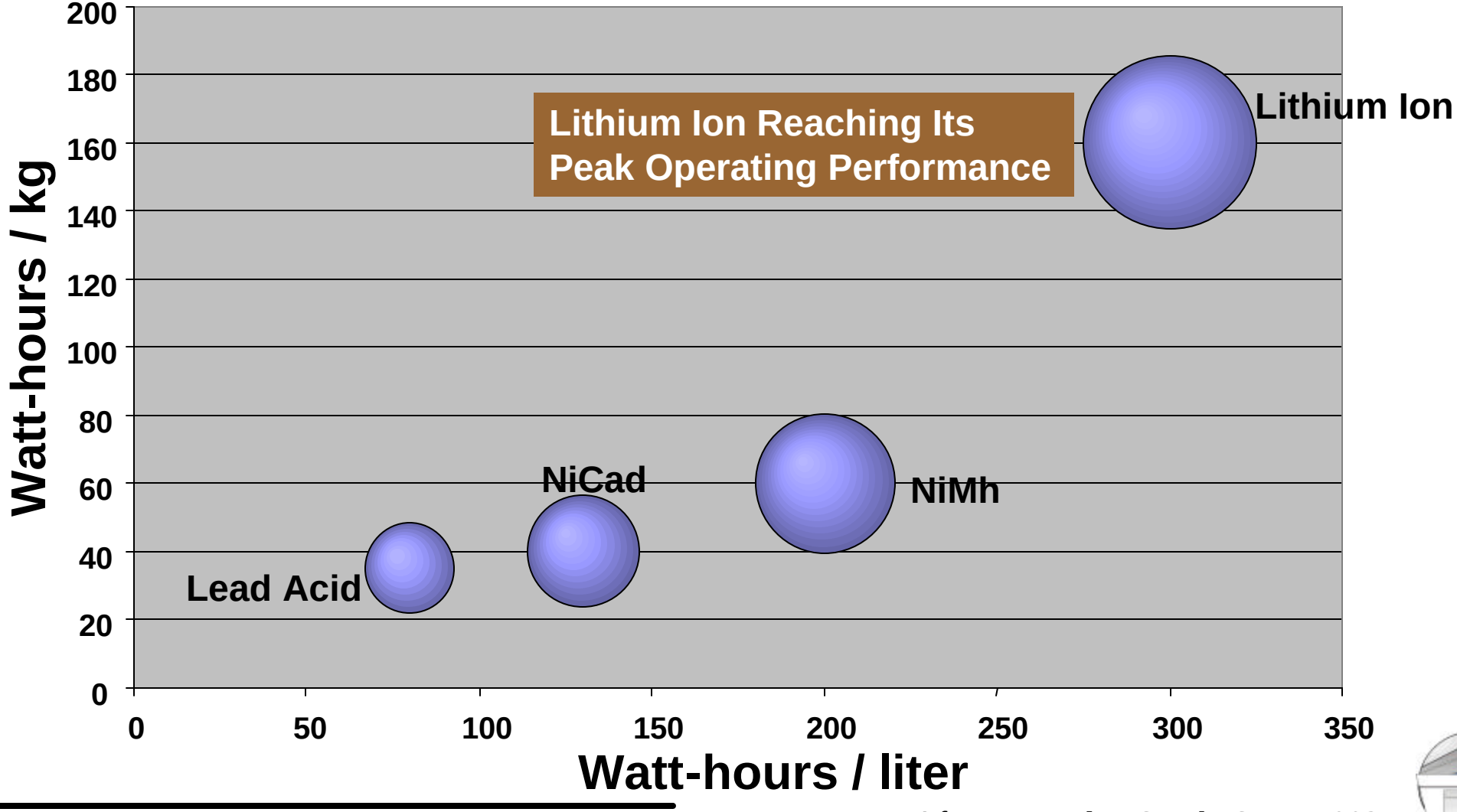
Ballard Power Systems

FUEL CELL APPLICATIONS

Battery Performance Comparison

Gravimetric (Specific Energy) vs.
Volumetric (Energy Density)

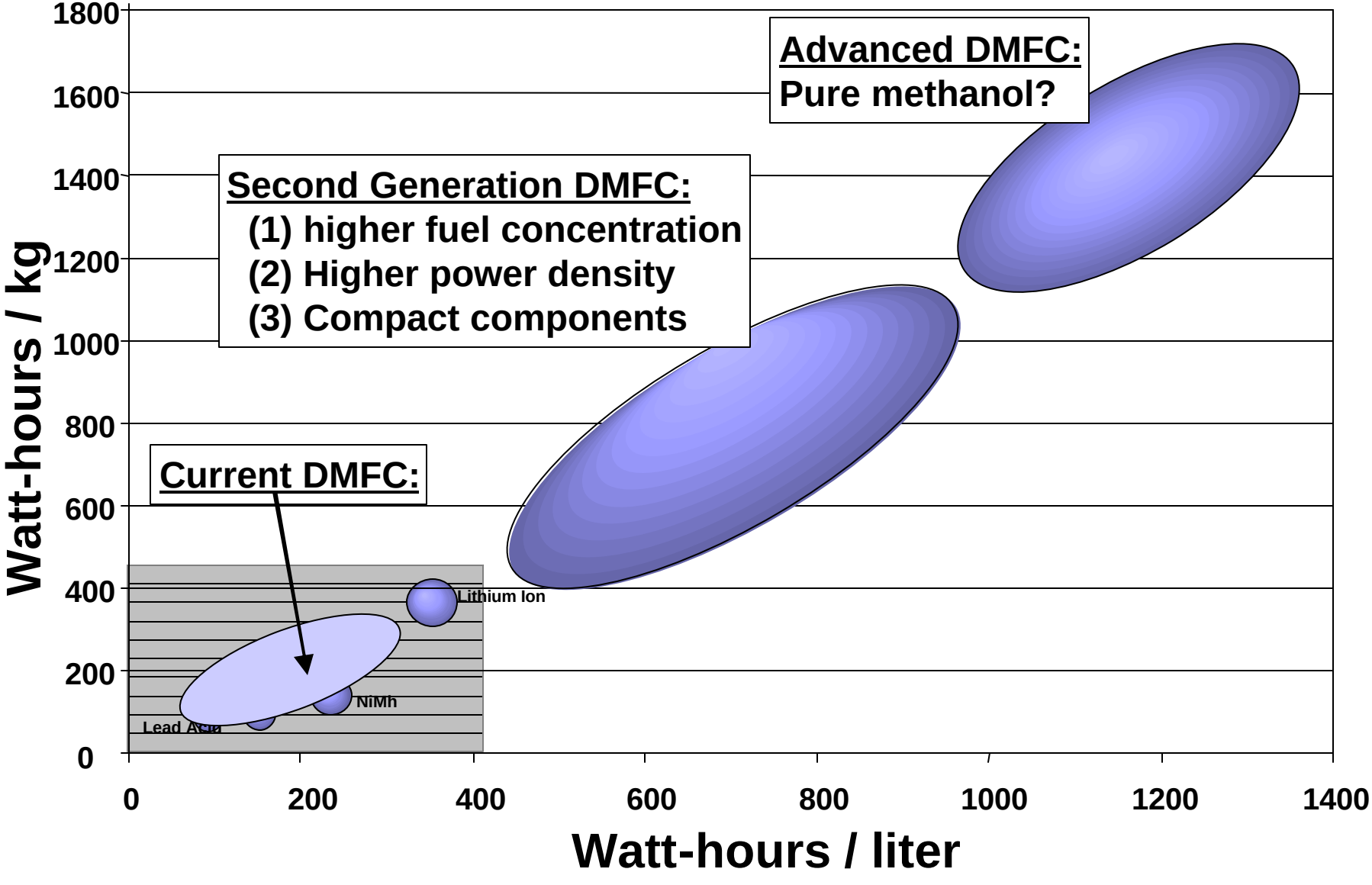
Fuel Cell (Pure Methanol)
1673 w hrs / kg
2086 w hrs / liter



After: Hampden-Smith, SMP, 2003

FUEL CELL APPLICATIONS

DMFC Performance and Projections



From: Kelty, Panasonic, 2003

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SOME RECENT DEVELOPMENTS

STATIONARY POWER

Plug Power

- Over 300 systems tested to-date
- Stack life demonstrated to > 9,000 hrs.
- Guaranteed/warranted product available

Plug Power

UTC Fuel Cells

- Over 250 PAFC systems installed to-date
- Guaranteed/warranted PAFC product available
- Stack life demonstrated to > 40,000 hrs.
- Significant advancement of PEM systems for stationary power

UTC Fuel Cells

SOME RECENT DEVELOPMENTS

STATIONARY POWER

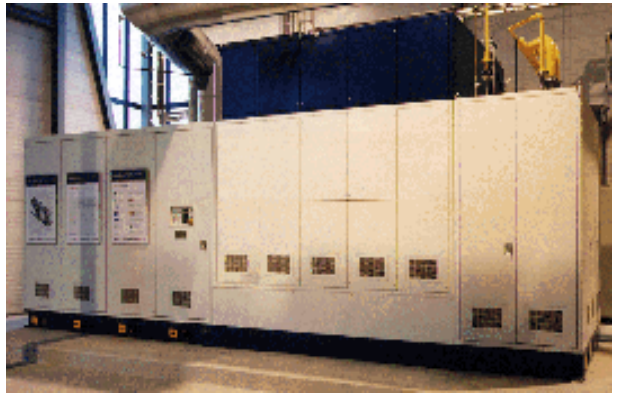
FuelCell Energy

- Testing DFC300™ and DFC1500™ (MW class) power plants
- Stack life demonstrated to > 25,000 hrs.
- Guaranteed/warranted product available
- New manufacturing capabilities (50MW/yr ® 400MW/yr)

FuelCell Energy

Siemens Westinghouse Power Corporation

- Demonstrated tubular SOFC life > 100,000 hrs.
- Demonstrated TSOFC systems at >14,000 hrs. with negligible degradation
- Built new manufacturing facility



Siemens Westinghouse

SOME RECENT DEVELOPMENTS

FuelCell Energy–Direct FuelCell™/Turbine Hybrid System

- **Objectives**
  - Design a 40 MW FC/T hybrid
  - Test sub-MW prototypes
- **280 kW system completed 6,740 hrs. of testing**
  - Efficiency of 52%
  - NOx & SOx below 0.1 ppm
- **Future Plans**
  - Fully integrated hybrid system w/ 60 kW Capstone for a demo in Montana
  - 40 MW power plant design

SOME RECENT DEVELOPMENTS

Siemens Westinghouse – TSOFC–Gas Turbine Hybrid System

- **Objectives:**
  - Demonstrate technical feasibility of PSOFC-GT
  - Demonstrate high efficiency (45 – 60 %) of SOFC hybrids
- **World's first SOFC Hybrid**
  - 3000 hrs. of operation
  - Pressurized operation
  - 53 % efficiency
- **Future Plans**
  - Commercialize atmospheric pressure CHP250 systems
  - Optimize GT & SOFC configuration for commercialization by 2010

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- **Transportation**
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SOME RECENT DEVELOPMENTS

Significant CaFCP Events:

- Road Rallies (2002, 2003)
- Significant Meetings/Conferences Support
- FCV Ride & Drives throughout state
- Cross Country FCV demonstration
- Etc.

SOME RECENT DEVELOPMENTS

IN TRANSPORTATION FUEL CELLS THIS YEAR:

- UPS, DaimlerChrysler to test FCV fleet in Michigan (May, 2003)
- DaimlerChrysler opens FCV Test Facility in Japan (April, 2003)
- National Automotive Center (NAC) introduces class-eight Freightliner truck with methanol-APU (April, 2003)
- Daihatsu tests its new mini MOVE FCV on public roads (Feb, 2003)
- GM Unveils Military Truck With Fuel Cell APU (Feb, 2003)
- FedEx and GM agree to test delivery vans in Tokyo (Jan, 2003)
- Hydrogenics agrees to work with John Deere (Jan, 2003)
- Nissan works with UTC Fuel Cells to unveil new FCV (Jan, 2003)
- UTC FC and NAVC test hybrid bus in CA (Dec, 2002)
- General Dynamics delivers FC APU to SunLine Transit (Dec, 2002)
- Toyota and Honda lease FC vehicles in CA (Dec, 2002)
- Hydrogenics FC APU to TACOM (Dec, 2002)
- GM Introduces the Hy-Wire concept (Sept, 2002)
- NECAR 5 Completes Cross-Country Trip (July, 2002)
- Toyota introduces FCHVs in Japan (Sept, 2002)
- Ford unveils new Focus FCV (July, 2002)
- GM Demonstrates gasoline FC S-10 Pickup (June, 2002)

Note: Only a representative, partial list

SOME RECENT DEVELOPMENTS

University of CA (UCI and UCD) Become First Customers for Toyota Fuel Cell Hybrid Vehicle – Dec 2, 2002

- Establish CA fuel-cell "community" partnerships to address product, infrastructure and consumer-acceptance issues
  - 80 kW motor (90 kW stack)
  - 180 mile range
  - 96 mph top speed
  - Seating for five people
  - Will lease 20 FCVs in next few months (10 in CA)

City of Los Angeles Becomes First Customer for Honda Fuel Cell Vehicle – Dec 2, 2002

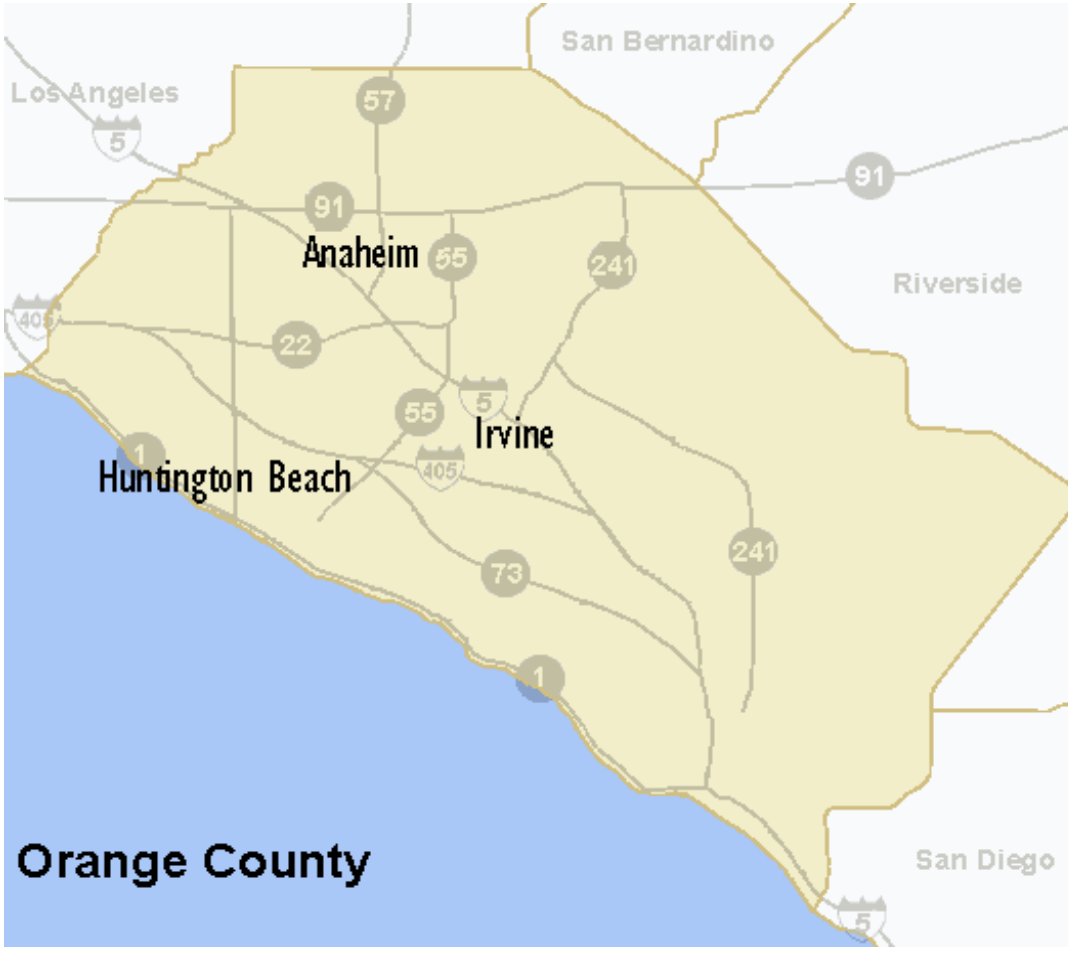
- Five Honda FCX vehicles leased by the City of Los Angeles, the first of which was delivered on December 2, 2002.
  - 60 kW motor
  - 220 mile range
  - Seating for four people
  - In the next two to three years, Honda expects to lease 30 cars in CA.

SOME RECENT DEVELOPMENTS

HYDROGEN INFRASTRUCTURE

Goals

- Catalyze Initiation of Infrastructure
- Educate Municipalities, Fire Marshals
- Facilitate Interface Between DG and Hydrogen Future



Strategic Alliance

- UCI
- AQMD
- Air Products and Chemicals, Incorporated
- Cities of Irvine, Anaheim, Huntington Beach
- The Irvine Company
- Toyota

SOME RECENT DEVELOPMENTS

HYDROGEN INFRASTRUCTURE

- Liquid H2 supply
- Capacity for 5 fillings per day
- Fill to 5,000 psig; Design will allow for future upgrade to 10,000 psig
- Truly public access (i.e., dispenser not behind locked gate)

SOME RECENT DEVELOPMENTS

Refueling Photos

SOME RECENT DEVELOPMENTS

TRANSPORTATION FUEL CELL ISSUES

Designed as hybrid (w/ battery storage) or direct electric drive

Pressurized vs. atmospheric operation

Competing (forerunning) technologies incl. hybrid ICE & H_2 ICE

Operational Challenges

- **Freezing of stack and cold weather operation**
- **Dry, hot weather operation**
- **Heat exchanger performance / size**
- **On-board hydrogen storage performance**
- **Dynamic operation**

Major hurdles

- **COST (Need less than ~$50/kW for engine)**
- **Infrastructure (fuel choice)**
- **On-board or distributed reformation (if needed)**
- **Hydrogen storage**
- **Hydrogen production and delivery pathway, costs, impacts**
- **Safety**

SOME RECENT DEVELOPMENTS

HYDROGEN STORAGE

High pressure hydrogen tank

Issue: Volume

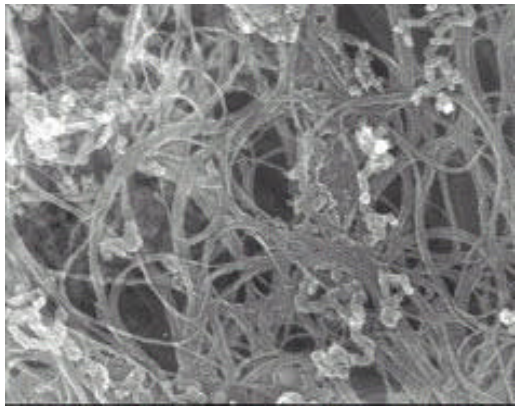
Hydrogen-absorbing alloy tank

Weight

Liquid hydrogen tank

Boil-off gas

Carbon nanotubes

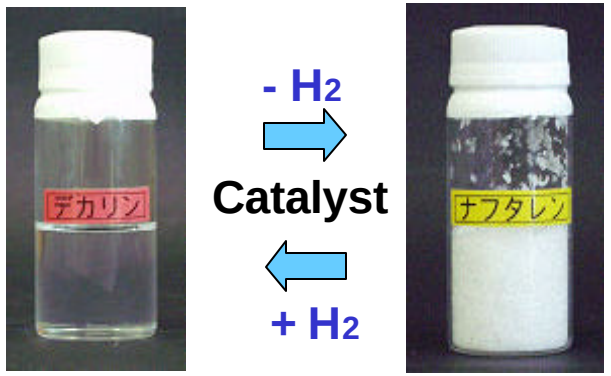


Issue: Actual storage capability?

Chemical hydrides

$NaBH_4$

Decalin($C_{10}H_{18}$) **Naphthalene($C_{10}H_8$)**



Handling / Recycling

Courtesy: Toyota, May, 2003

Presentation Outline

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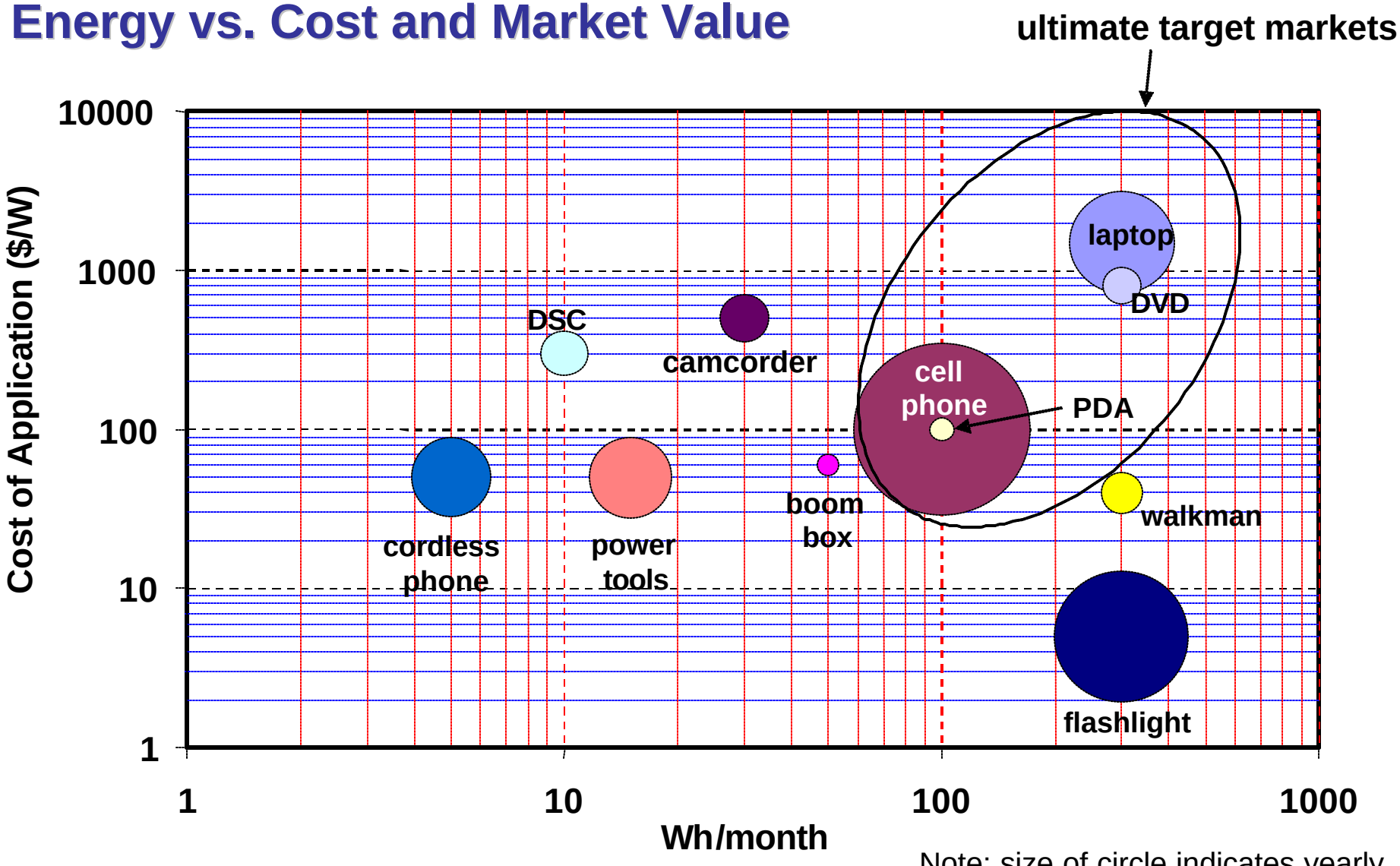
- Stationary Power
- Transportation
- **Portable Power**
- Other

Summary

FUEL CELL APPLICATIONS

Energy vs. Cost and Market Value

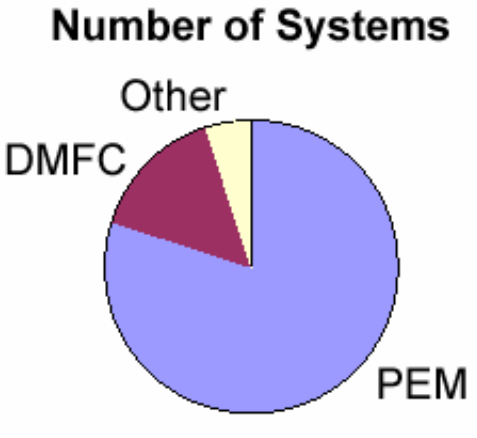


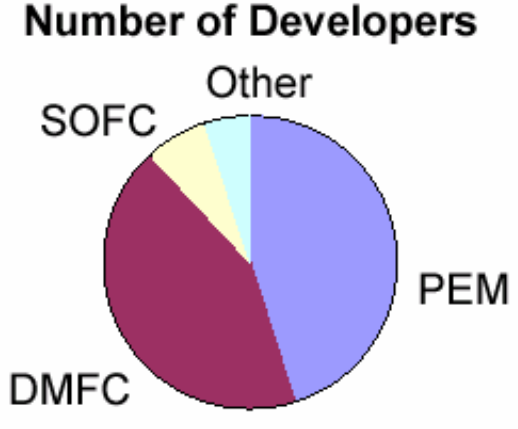
Note: size of circle indicates yearly market value of batteries

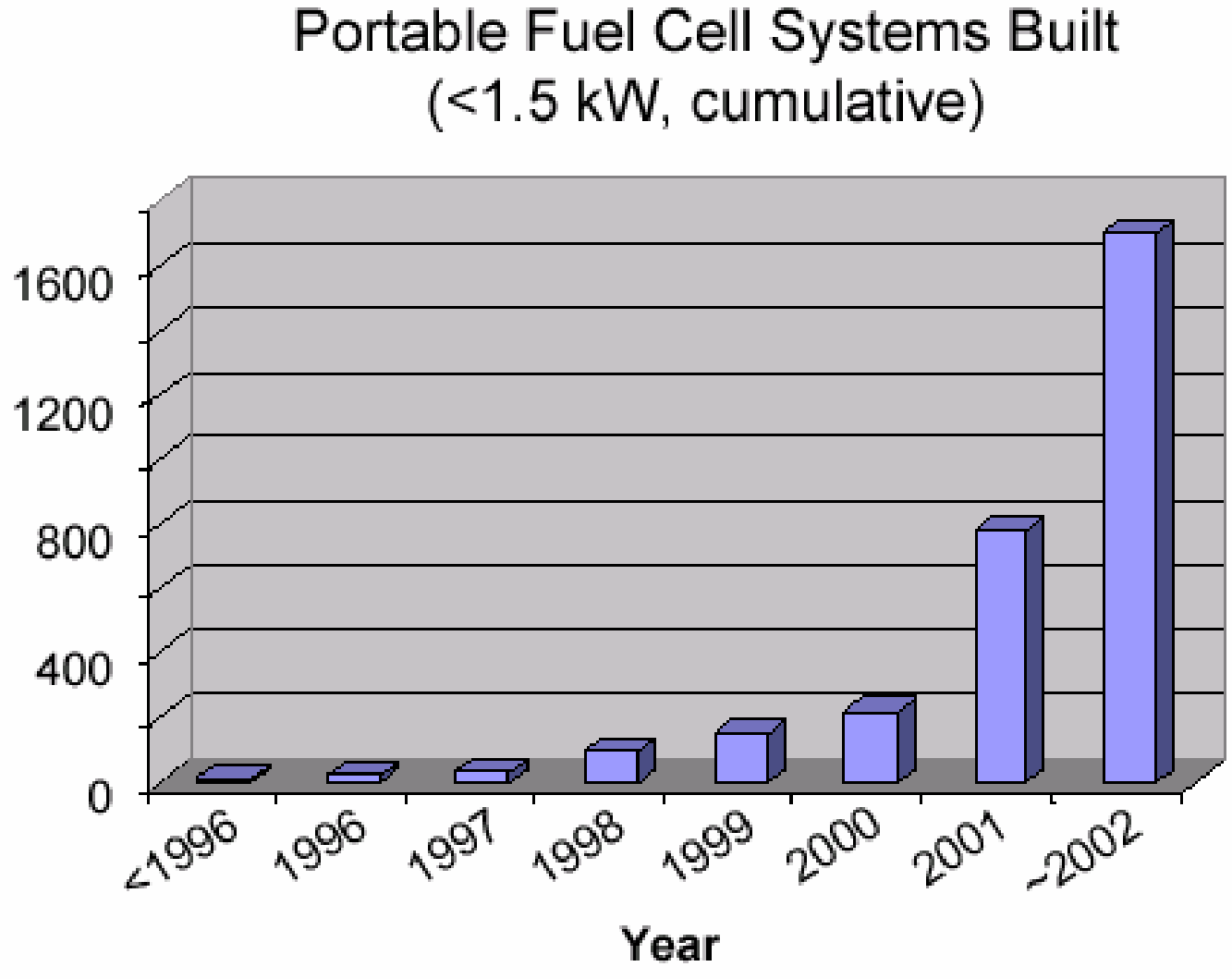
Source: Panasonic, Portable Fuel Cell Conference, May 2003

SOME RECENT DEVELOPMENTS

PORTABLE POWER FUEL CELLS







Source: Fuel Cell Today, 9/02

SOME RECENT DEVELOPMENTS

PORTABLE POWER FUEL CELL ISSUES

PEMFC

- Platinum & material costs need to be dramatically reduced
- CO tolerance required
- Fuel may not be allowed on planes

DMFC

- Platinum & material costs need to be reduced
- CO tolerance required

SOFC

- Larger portable (~1 kW)
- Potentially low material costs
- Costly manufacturing
- Dynamic / cyclic performance

Metal Air

- Often equated with a flow battery
- High specific energy
- Potentially low material costs

SOME RECENT DEVELOPMENTS

PORTABLE POWER FUEL CELL ISSUES

- Limitation of methanol concentration
- Low fuel efficiency
- Low catalyst activity & catalyst degradation
- Life cycle costs & impacts
- Heat management
- Fuel / air delivery system
- Fuel / water recycling
- Noise reduction
- Orientation sensitivity
- Miniaturization
- High materials and manufacturing costs
- Codes & Standards plus standardization (e.g., fuel cartridge)
- Customer's habits – consumer acceptance

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SOME RECENT DEVELOPMENTS

Aircraft-based & High Altitude Fuel Cells

SOFC or PEM as an Auxiliary Power Unit (APU) for commercial aircraft:

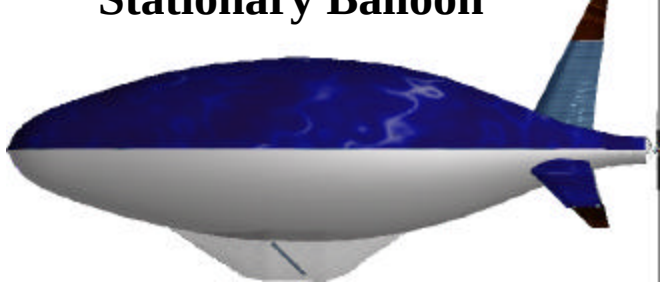
- Less fuel burned
- More main engine power available for propulsion
- Longer, cheaper missions
- Less pollution

High altitude, unmanned, long endurance missions

- Communications (voice, data, media)
- Surveillance (radar, optical)

Helios Aircraft (Solar – Regenerative FC)

Stationary Balloon

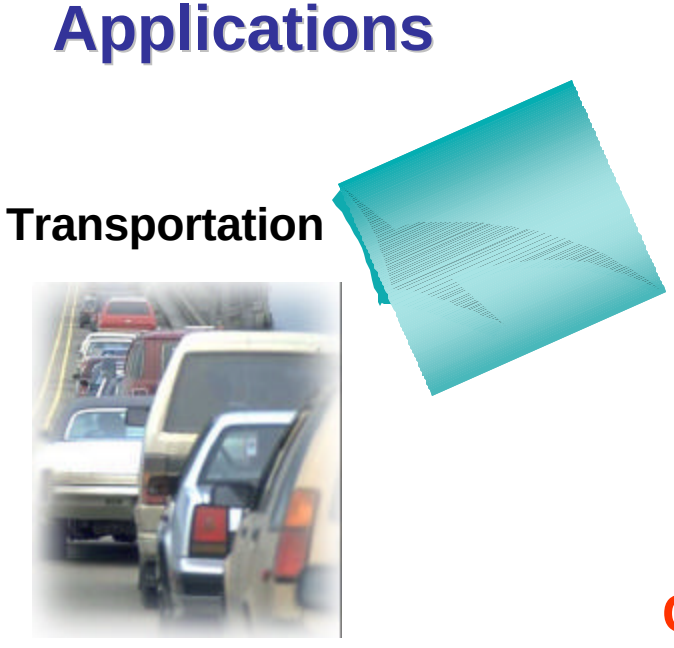


Courtesy of NASA and Boeing

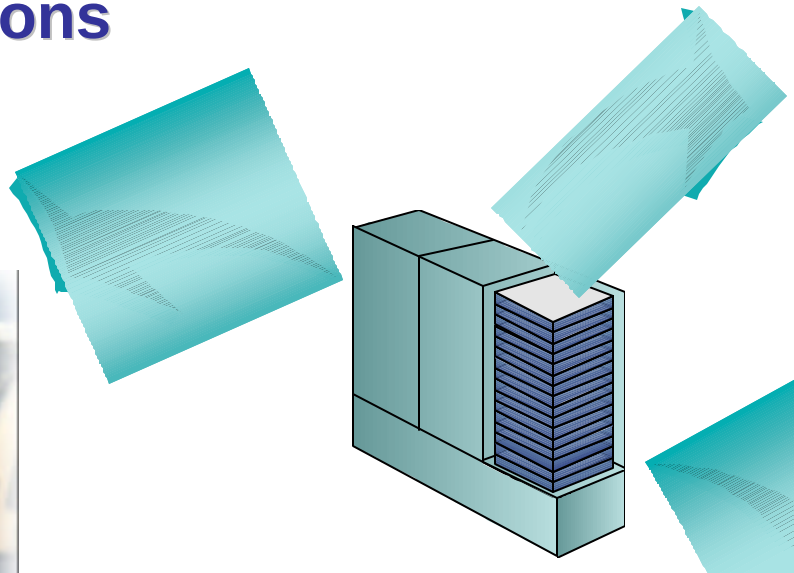
SOME RECENT DEVELOPMENTS

Solid State Energy Conversion Alliance (SECA):

- Led by NETL, PNNL
- A High Power Density, Low Cost Core Module for Multiple Applications



Transportation



Core Module

Stationary Power

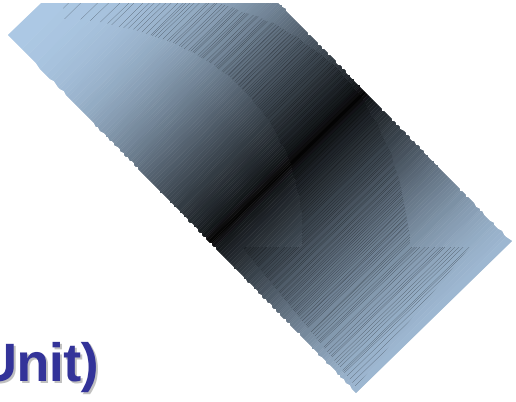
Military

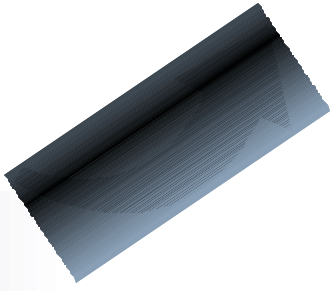
Key to Cost Reduction:
Mass Customization of Common Modules

After: Mark Williams, U.S. DOE, 2002

SOME RECENT DEVELOPMENTS

SECA: Progressive Applications





2005

$800/kW

Prototype (b-Unit)
3 - 10 kW

2010

$400/kW

Commercial

2015

Vision 21 Power Plants

70-80% efficient plants

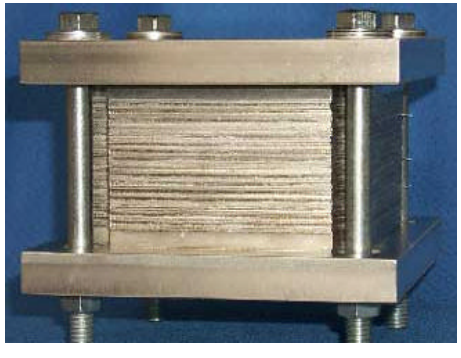
Propulsion <$200?/kW

After: Mark Williams, U.S. DOE, 2002

SOME RECENT DEVELOPMENTS

SECA PHASE III

- Power Rating Net = 3-10 kW
- Cost = $400 / kW
- Efficiency (AC or DC/LHV)
  - 30 - 50% [APU]
  - 40 - 60% [Stationary]
- Steady state testing (>1500 hours)
  - 95% availability
  - Power <0.1% degradation/500 hours
- Transient testing (>100 cycles defined by application)
  - Power < 1% degradation after 100 cycles
- Design Lifetime = 5,000 Hours (APU), 40,000 Hours (Stationary)
- Maintenance Interval > 1,000 Hours
- Fuels
  - Natural Gas
  - Gasoline
  - Diesel



After: Mark Williams, U.S. DOE, 2002

SOME RECENT DEVELOPMENTS

Six SECA Industrial Teams

SIEMENS Westinghouse

DELPHI
Driving Tomorrow's Technology

Battelle

General Electric Company

Cummins Power Generation

SOFCo

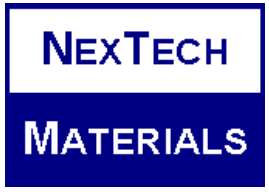
FuelCell Energy, Inc.

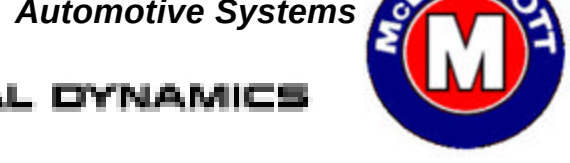
Accu:metrics®

GENERAL DYNAMICS
C4 Systems

SECA Participants

Universities, National Labs, Industry





After: Mark Williams, U.S. DOE, 2002

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Summary

- Fuel cell technology has been greatly advanced in the last decade
- Significant investment of government and industry
- Primary applications include stationary power, transportation and portable power
  - Stationary fuel cell systems are commercial today
  - More than 100 fuel cell vehicle prototypes have been tested and demonstrated to-date
  - Portable fuel cells have tremendous promise vs. batteries
- Exciting potential advancements in key application categories should be expected in very near future:
  - Vehicle PEM systems
  - SECA SOFC systems (stationary power, APU)
  - Portable Power PEM/DMFC systems
- Major hurdle is still cost reduction – recent advances portend bright future for fuel cells